

# COMPARISON OF NUMERICAL MODELS FOR VIBRO-ACOUSTIC ANALYSIS OF STRUCTURAL PANELS IN LOW MODAL DENSITY RANGE ENGAGING AIR LAYERS

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## ABSTRACT

During launch, satellite and their equipment are subjected to loads of random nature and with a wide frequency range. Their vibro-acoustic response is an important issue to be analysed, for example for folded solar arrays and antennas. The main issue at low modal density is the modelling combinations engaging air layers, structures and external fluid. Depending on the modal density different methodologies, as FEM, BEM and SEA should be considered. This work focuses on the analysis of different combinations of the methodologies previously stated used in order to characterise the vibro-acoustic response of two rectangular sandwich structure panels isolated and engaging an air layer between them under a diffuse acoustic field. Focusing on the modelling of air layers, different models are proposed. To illustrate the phenomenology described and studied, experimental results from an acoustic test on an ARA-MKIII solar array in folded configuration are presented along with numerical results.

## 1. INTRODUCTION

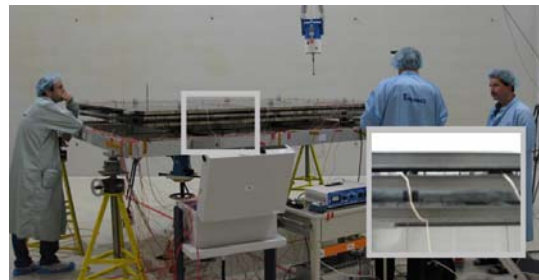
The numerical models for simulating the response of spacecraft structures have evolved along with the general optimization of these structures, in particular due to the evolution of the main design loads considered. In the present designs the main loads concerned are those derived from the shock loads and from the structure-fluid interaction, which are known as acoustic loads.

This work is focused on the design of low frequency models of a structural system that arise commonly in space-oriented structures: structural panels separated by thin air layers, (as those present in solar arrays in the folded configuration or between different equipment platforms [1]). The main issue in these configurations is the influence of the air layer as a dynamic coupler between the structural elements that greatly affects to the dynamic behaviour of the system, especially in the first eigenfrequencies [2,3].

The need of developing a numerical model which is able to reproduce these low frequency considerations while being compatible with numerical models focused on solving higher frequencies is one of the main issues to be considered [4].

The inclusion of air layers in the work models used in the industry has changed: from the use of qualitative

and simplified models to the need of implementing these elements in the fine-tuned numerical models of the commercial codes used. To approach the modelling of these structures, several numerical techniques can be considered for both structural and fluid domains and for both ranges of frequency and modal density (deterministic and stochastic) [5]. The most widely used methods are: Finite Element (FEM), Boundary Elements (BEM) Methods and Statistical Energy Analysis (SEA). These formulations have to be considered to model the different elements present in the problem: the structural panels, the air layer between them and the surrounding air.



(Source: Courtesy of Dutch Space, 2009)

Figure 1. Dutch Space ARA-MKIII solar array in folded configuration. Close up shows the gap thickness between panels.

Given the particularities of the structure and the available techniques to apply in a numerical model, several combinations of the three methodologies previously stated can be considered to simulate the response of the system under external loads. Six combinations of the numerical techniques will be presented in order to evaluate and show the main differences between them.

In order to evaluate the efficiency of the proposed configurations, two indicators will be presented: the dynamic behaviour (in terms of the frequency response to a nominal unitary random structural load) and the vibro-acoustic behaviour (structural response under a diffuse acoustic field).

As the problem presented (thin air layers between structural elements) is common in solar arrays in folded configuration, these structures will be taken as the general definition of the problem and as a benchmark case inspired by the general configuration and properties of such systems will be defined in order to implement the proposed numerical configurations.

The present paper is structured as follows: a set of proposed numerical configurations will be proposed for the problem stated; a benchmark case to be considered as system which response is going to be simulated will be defined in terms of geometry, mechanical properties and dynamic response; the efficiency of the proposed numerical configurations through their application to the benchmark case will be obtained, considering the simulated response regarding the general behaviour of actual specimens from experimental results, leading finally to a set of conclusions.

## 2. PROPOSED MODELLIZATIONS

The numerical techniques that are most widely considered in vibro-acoustic models are: FEM and BEM for low modal density and SEA for high modal density. Therefore, these three techniques are considered for proposing several configurations in the simulation of the problem.

Depending on the modal density: structural elements are usually modelled through FEM or SEA and the air layer between the structural elements are usually modelled through FEM, BEM or SEA. Finally, the surrounding air is usually modelled through BEM or SEA depending on the frequency range although a SEA approach in the low frequency range can be considered depending on other factors as the interest of the response in the fluid domain. Under these considerations, a set of six numerical techniques configurations are considered as summarised in Tab. 1 and sketched in Fig. 2.

Table 1. Set of proposed numerical techniques configurations considering FEM, BEM and SEA as methodologies to simulate the system compound of two structural panels separated by an air layer and an external air surrounding them.

Configuration	Plate	Air Layer	External Air
A	FEM	FEM	BEM
B	FEM	FEM	SEA
C	FEM	BEM	BEM
D	FEM	SEA	SEA
E	SEA	SEA	SEA

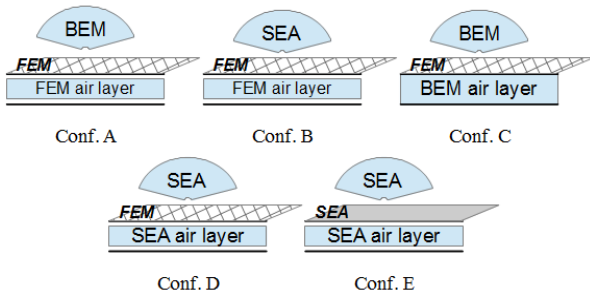


Figure 2. Proposed configurations considering FEM, BEM and SEA methodologies to simulate the system compound of two structural panels separated by an air layer and an external air surrounding them.

Additional configurations in which the structural panels are SEA subsystems, the air layer a FEM element and the surrounding air as an energetic unbounded semi-space might be considered. Given restrictions on the

commercial package used (VA One) this model is not considered within this work.

## 3. BENCKMARK CASE DEFINITION

A solar array is composed of several solar wings, usually constructed in an aluminium core and CFRP skin sandwich structure. The thickness of these structural elements is of the order of a couple of centimetres and in folded configuration they are spaced by a distance of the same order of magnitude. This leads to a great coupling between the structural elements due to the resulting thin air layer. As example, the ARA-MKIII solar array developed by Dutch Space consists of several solar wings made up of aluminium honeycomb core with CFRP skins (length to width ratio of 1.2 and thickness of 22 millimetres) that are separated in the folded configuration by 11 millimetres.

From this approximated description of a typical solar wing a benchmark case is defined to be simulated. In order to compare in later sections with experimental results from the stated actual specimen, a benchmark solar wing is defined: a sandwich panel of aluminium honeycomb core with CFRP skins with a thickness of 22.5 millimetres. The mechanical properties of the structural element have been selected from typical values of density and stiffness of present sandwich structures designs for solar arrays.

The benchmark case to study will be defined as a simplified case of the solar array in folded configuration: two solar wings separated by an air layer 50 millimetres thick. In order to avoid the influence of the actual mechanical elements joining both solar wings and to consider only the effect of dynamic coupling and load transmission path due to the thin air layer, no mechanical connection between the wings is included in the model.

As stated, the response of the defined benchmark structure will be simulated to analyse its response from two points of view: the dynamic behaviour and the vibro-acoustic behaviour. To this end, two reference loads must be defined: A structural load consisting of a random unitary punctual load applied in one of the structural panels and an acoustic load consisting of a constant 1 Pa sound pressure diffuse field. The first one will show the dynamic behaviour of the system pointing out the influence of the air layer as dynamic coupler.

### 3.1 Characterisation of benchmark case

In order to evaluate the influence of the air layer in the system response, this section presents a characterisation of the elements of the system in terms of their dynamic response. Therefore, numerical models were developed in order to simulate both elements of the system: the structural panel and the air layer. As the main interest of the behaviour of the system as a whole is the low frequency range, the numerical models for the characterisation were developed through FEM (structural and fluid element) and BEM (fluid element).

The dynamic behaviour of the structural element in the low frequency range is studied through its frequency response to a unitary random punctual load to define the first eigenfrequencies of the system. This dynamic response will be analysed in later sections under the influence of the air layer. An analogous response for the air layer is obtained from a numerical model based in FEM and BEM, in this case under a 1 Pa sound pressure diffuse field.

Fig. 3 shows the simulated response of the system to a punctual 1 N random load, measured through the spatial mean response in the whole panel in the frequency space. The first eigenfrequencies of the structural element are summarised in Tab. 2.

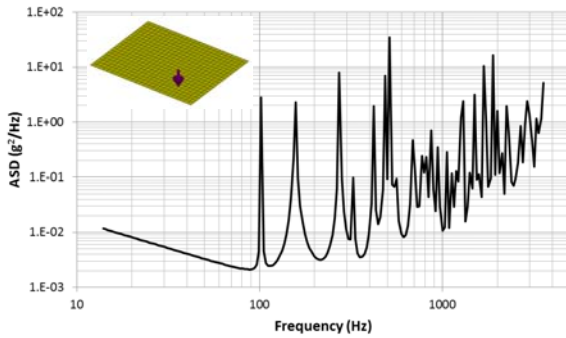


Figure 3. Spatial mean structural response ( $g^2/Hz$ ) of the structural panel in 1/24th octave bands for a punctual load consisting in a 1 N random spectrum applied in an asymmetry point (displayed).

Table 2. First eigenfrequencies of the structural panel

# Eigenvector	Eigenfrequency (Hz)
1	102.1
2	157.5
3	272.7
4	324.2
5	420.5
6	485.8

Table 3. First eigenfrequencies of the 50 mm thickness air layer between the structural panels

# Mode	Eigenfrequencies (Hz)
1	137.3
2	171.6
3	219.9
4	274.9
5	324.4
6	343.9
7	370.6

The dynamic behaviour of the air layer can be determined by means of two different approaches, depending on the technique applied: FEM fluid cavity and a BEM fluid cavity delimited by rigid faces. The first one is analysed through an eigenvalues analysis and the second one through the dynamic response to a 1 Pa pressure diffuse acoustic field. Both models correspond to an air layer of 50 millimetres thickness. The

differences between both families of eigenfrequencies are negligible and their value is shown in Tab. 3.

#### 4. DYNAMIC BEHAVIOUR OF THE BENCHMARK CASE

As stated in the introduction, one of the main effects of the air layers is the modification of the dynamic response of the system with respect to the vacuum condition, in general showing a trend of decrease of the first eigenvalues. To analyse this effect, the benchmark case is modelled through the several configurations proposed. This section presents the simulated dynamic behaviour of the system analysing the mean spatial response of the structural elements under a constant 1 N random point force.

The frequency range considered for the simulated response of the system ranges from the 16 Hz to the 3150 Hz 1/3th octave bands. Fig. 4 depicts the simulated response for the five proposed configurations. Nevertheless, given the higher interest in the first eigenfrequencies, this section will focus on the frequency range around 100 Hz and in configurations A, B, C and D.

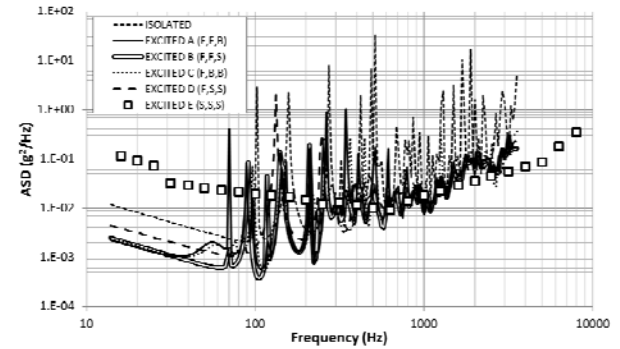


Figure 4. Simulated spatial average response ( $g^2/Hz$ ) of the excited structural element in the proposed configurations for a punctual load consisting in a 1 N random spectrum applied in an asymmetry point of one of the panels (for reference, response of the isolated element is shown).

As previous studies have shown [6], the thickness of the air layer is critical for the dynamic response of the system. Therefore, the accuracy of this dimension in the proposed configurations must be analysed before considering the global response of the system. The modelling of the air layer through FEM or SEA allows for accounting for the actual air layer thickness while the BEM imposes the air layer thickness to be the distance between the middle planes of the structural elements. This difference is illustrated in Fig. 5 which shows sketches for configurations A, C and D displaying the structural elements as their middle plane as in the actual numerical models.

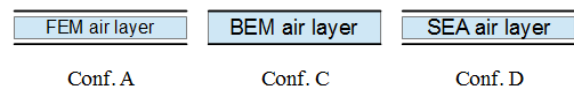


Figure 5. Sketches of configurations A, C and D representing the structural elements through their middle planes to point out the actual air layer thickness.

The global effects of the air layer thickness are not slight. Fig. 6 shows the FRF of the benchmark case for configurations A, C and a modified configuration A (A\*) in which the FEM air layer has the same thickness of the one in configuration C.

As can be seen, the modification of the first eigenfrequency with the air layer thickness is consistent between FEM and BEM air layers for same thickness although it does not correspond to the actual air layer. Given this influence, configuration C will not be considered in the following and the study will focus on configurations A, B, and D.

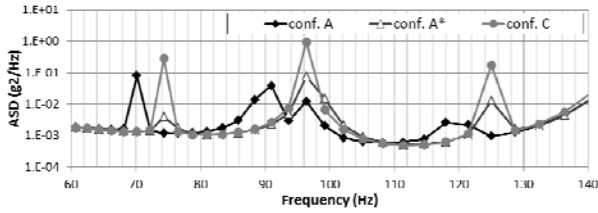


Figure 6. Variation of the first eigenfrequency with the thickness of the air layer considering the actual air layer thickness (conf. A) or not (conf. C and conf. A\*). Graph shows the spatial averaged response of the structural element in 1/24th octave bands for a 1 N point random load in an asymmetry point.

Configuration D requires additional remarks regarding the applicability of the SEA methodology for the air layer in the frequency range considered. The characteristic modal density for the air layer as shown by its characterisation is below the accepted values for applicability of SEA and additional concerns will be required.

Then, the dynamic behaviour of the system at low frequencies is studied through the numerical simulation of configurations A, B and D under the unitary random point load in a frequency spectrum of 1/24<sup>th</sup> octave bands. The spatial and frequency averaged response for both structural panels (the excited and the non-excited one) is shown in Figs. 7 and 8.

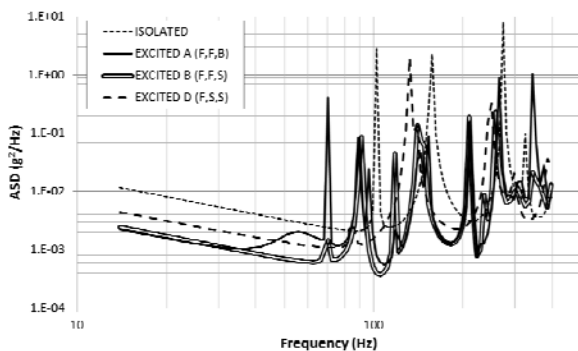


Figure 7. Simulated spatial average response ( $g^2/Hz$ ) of the excited structural element in configurations A, B and D computed in 1/24th octave bands for a punctual load consisting in a 1 N random spectrum applied in an asymmetry point of one of the panels (for reference, response of the isolated element is shown).

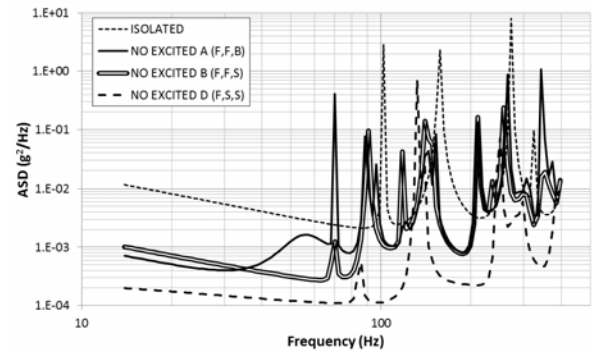


Figure 8. Simulated spatial average response ( $g^2/Hz$ ) of the non-excited structural element in configurations A, B and D computed in 1/24th octave bands for a punctual load consisting in a 1 N random spectrum applied in an asymmetry point of one of the panels (for reference, response of the isolated element is shown).

Both results evidence the influence of the air layers in the dynamic behaviour of the system, showing clearly the contribution of the air layer as coupler of both structural elements. Two effects are identified: decrease of the first eigenfrequencies and the increase in the number of them. This agrees the trends identified in experimental determination on specimens with thin air layers engaged as solar arrays in folded configuration.

Tab. 4 summarizes the main eigenfrequencies for an specimen of the Dutch Space ARA-MKIII solar array. Two sets are considered: numerically determined through a FEM model considering only the structural components and experimentally through a test campaign performed in the IABG GmbH within the VAA-TM-LDS ESA project [7].

Table 3. First eigenfrequencies of the ARA-MKIII solar array determined numerically (FEM model considering only structural elements) and experimentally (through modal test campaign).

# Eigenvector	FEM model (only structure)	Modal testing on actual specimen
1	81	13
2	108	19
3	140	26

The compared results show the decrease of the eigenfrequencies due to the interaction between the structural elements and the air layer.

The efficiency of the numerical configurations proposed can be evaluated taking into account this trend towards the decrease and multiplication of the first eigenfrequencies. These two effects are only present in the response of configurations A and B in which the air layer is modelled through FEM.

Configuration D, in which the air layer is a SEA subsystem, is only able to represent the role of the air layer as a load transmission path. The latter is driven by the non-resonant behaviour of the SEA air layer in this frequency layer. At higher frequencies, as its modal density increases, a better agreement between configurations is found.

## 5. VIBRO-ACOUSTIC BEHAVIOUR OF THE BENCHMARK CASE

The vibro-acoustic response of the proposed models are analysed through the dynamic response of the system to an external acoustic load. The acoustic load considered is a uniform sound pressure of 1 Pa. In order to model this load in the proposed numerical models, two considerations have to be made: the region of application and the numerical technique to apply.

Within this work, the external load is considered to excite only the external faces of the structural elements. The acoustic load is supposed not to excite neither the internal plate faces (those next to the air layer) nor the air layer itself.

The diffuse acoustic field will be modelled through two methods depending on the modelling of the surrounding air. For BEM fluids it will be modelled as a set of 50 acoustic plane waves of weighted intensity. For SEA semi-infinite fluids the acoustic load will be modelled through an analytical formulation based on a diffuse-field reciprocity theorem [8,9].

As for the dynamic behaviour, the response of the structural elements under the external load is analysed. As the case considered corresponds to the symmetric transmission problem, only the response of one of the structural element will be presented (Fig. 9). Then, the analysis will focus again in the role of the air layer as dynamic coupler over the one as load transmission path.

As for the previous case, the same conclusions on the efficiency of the proposed numerical configurations in reproducing the role of the air layer as dynamic coupler are extracted: configurations A and C show this effect but not configuration D. The same agreement is found as the modal density of the air layer increases.

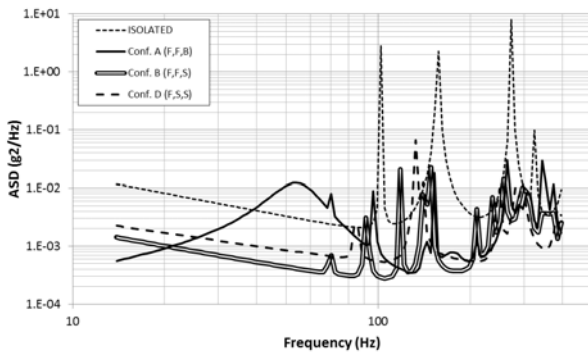


Figure 9. Mean response of the structural elements ( $g^2/Hz$ ) for proposed numerical techniques configurations A, B and D computed in 1/24th octave bands for an acoustic load consisting in a diffuse acoustic field of a pressure of 1 Pa exciting the external faces of the structural elements

The interest of the vibro-acoustic response of these systems is not restricted to the low frequency range and the interest covers the high frequency range. From the proposed models, only configuration E is defined on base to energetic elements for all the components (structural panels, air layer and surrounding air), therefore it's mainly focused in the high frequency

response. Applicability of SEA depends on different parameters (modal density, modal overlap, coupling between subsystems), nevertheless, the modal count of the benchmark case is above 5 for the structural element from 630 Hz and from 1600 Hz for the air layer. Fig. 10 shows the mean spatial response of the structural element under the diffuse acoustic field.

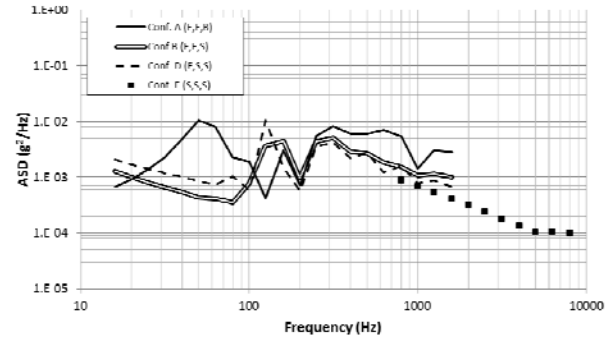


Figure 10. Spatial and frequency (1/3th octave bands) averaged response of the structural elements ( $g^2/Hz$ ) for proposed numerical techniques configurations A, B, D and E for an acoustic load consisting in a constant 1 Pa sound pressure diffuse field.

Results show a good consistency between the proposed models for the low frequency and the high frequency ranges. A better agreement is found in those models in which the surrounding air is modelled through an energetic formulation as the frequency increases. The derivation of hybrid models for this medium frequency range is studied in more detail in [10].

## 6. APPLICATION ON AN ACTUAL SOLAR ARRAY

The phenomenon posed is greatly amplified in an actual solar array in folded configuration due to the high number of elements. Dutch Space ARA-MKIII solar array is compound of three solar wings and two air layers. These structures were taken as reference for its definition and the general dimensions are quite similar: to the benchmark case: length to width ratio of the solar array wings is 1.2, the thickness of each solar wings is 22 mm and the separation between them is 11 mm.

This section presents the application of the proposed configurations to this case. The study is also in the dynamic response of the system as indicator of the coupling role of the air layer. A sketch and a FE model for the structural elements (solar wings, hinges and other components of the deployment system) are depicted in Fig. 12 and Fig. 13.

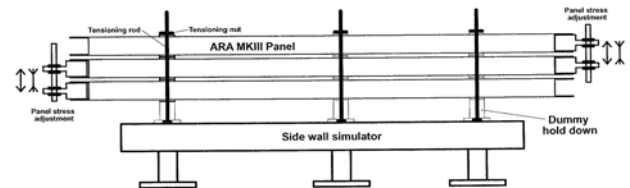


Figure 12. ARA-MKIII solar array in folded configuration.



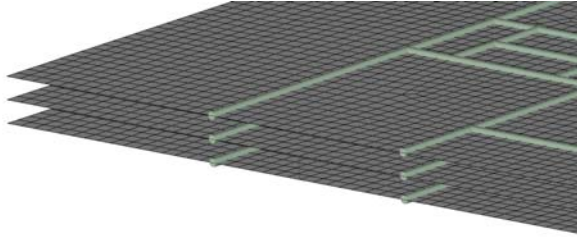
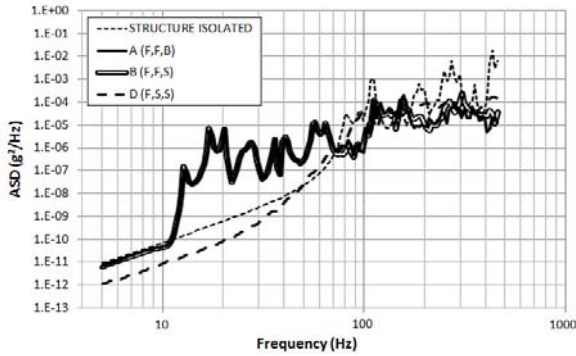


Figure 13. Close up of structural FE model for the ARA-MKIII solar array in folded configuration.

The dynamic response of a section of the middle solar wings under a constant point load is shown in Fig. 12 for a structural FE model (without considering the air layers) and for the three configurations proposed (A, B and D).



From these results the trend in the decrease of the first eigenfrequencies is clearly identified and the corresponding values are shown in Tab. 4.

Table 4 First eigenfrequencies of the ARA-MKIII solar array depending on the inclusion of the air layers of the analysis: Structural FE model, experimental modal test and a FE model including structure and air layers.

FEM model (Only str.)	Modal test on actual specimen	Conf.A and B Models
81	13	13
96	19	17
108	26	20
140	34	25
176	36	27
187	42	36
198	45	41

## 7. CONCLUSIONS

The problem of the interaction of thin air layers with structural elements has been presented from the approach of the numerical modelling. Considering a combination of the numerical methodologies most used is the scope of the work. The analysis of six proposed configurations (five for the low frequency range and one for the high frequency range) leads to establish the efficiency and accuracy of them in the analysis of these problems. The decrease of the first eigenfrequencies is the parameter to evaluate the efficiency and is considered that two configurations (A and B) best fit the phenomena. Regarding the high frequency range, the continuity in the frequency between the low and high frequency oriented configurations is studied for acoustic loads. The agreement between both ends is good even in

regions of lower modal count, improving with number of elements modelled through SEA in the model analysed.

## 8. ACKNOWLEDGMENTS

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